



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Setting an agenda for biofouling research for the marine renewable energy industry

Citation for published version:

Loxton, J, MacLeod, AK, Nall, CR, McCollin, T, Machado, I, Simas, T, Vance, T, Kenny, C, Want, A & Miller, R 2017, 'Setting an agenda for biofouling research for the marine renewable energy industry', *International Journal of Marine Energy*, vol. 19, pp. 292-303. <https://doi.org/doi.org/10.1016/j.ijome.2017.08.006>

Digital Object Identifier (DOI):

doi.org/10.1016/j.ijome.2017.08.006

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Version created as part of publication process; publisher's layout; not normally made publicly available

Published In:

International Journal of Marine Energy

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



Accepted Manuscript

Setting an agenda for biofouling research for the marine renewable energy industry

J Loxton, AK Macleod, CR Nall, T McCollin, I Machado, T Simas, T Vance, C Kenny, A Want, R Miller

PII: S2214-1669(17)30071-1

DOI: <http://dx.doi.org/10.1016/j.ijome.2017.08.006>

Reference: IJOME 173



To appear in:

Received Date: 19 May 2017

Revised Date: 11 August 2017

Accepted Date: 18 August 2017

Please cite this article as: J. Loxton, A. Macleod, C. Nall, T. McCollin, I. Machado, T. Simas, T. Vance, C. Kenny, A. Want, R. Miller, Setting an agenda for biofouling research for the marine renewable energy industry, (2017), doi: <http://dx.doi.org/10.1016/j.ijome.2017.08.006>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Setting an agenda for biofouling research for the marine renewable energy industry

Loxton J^{1*}, Macleod A K², Nall C R¹, McCollin T³, Machado I⁴, Simas T⁴, Vance T⁵, Kenny C⁶, Want A⁷, and Miller R²

¹*The Environmental Research Institute, University of the Highlands and Islands, Ormlie Rd, Thurso, KW14 7EE, UK. E-mail: [*jennifer.loxton@uhi.ac.uk](mailto:jennifer.loxton@uhi.ac.uk) ; chris.nall@uhi.ac.uk*

²*The Scottish Association for Marine Science (SAMS), Oban, PA37 1QA, UK; E-mail: raeanne.miller@sams.ac.uk; adrian.macleod@sams.ac.uk*

³*Marine Scotland, Marine Laboratory, 375 Victoria Road, Aberdeen, AB11 9DB, UK. E-mail: tracy.mccollin@gov.scot*

⁴*WavEC – Offshore Renewables, Rua D. Jerónimo Osório, n.º 11, 1º andar, 1400–119 Lisboa, Portugal. E-mail: ines.machado@wavec.org; teresa@wavec.org*

⁵*PML Applications Ltd, Prospect Place, Plymouth, PL1 3DH, UK. E-mail: thva@pml.ac.uk*

⁶*AlbaTERN Ltd, Midlothian Innovation Centre, Edinburgh, EH25 9RE, UK. E-mail: calum@albatern.co.uk*

⁷*International Centre for Island Technology, Heriot-Watt University, Back Rd, Stromness, Orkney, KW16 3AW, UK. E-mail: a.want@hw.ac.uk*

Abstract:

Extensive marine growth on man-made structures in the ocean is commonplace, yet there has been limited discussion about the potential implications of marine growth for the wave and tidal energy industry. In response, the Environmental Interactions of Marine Renewables (EIMR) Biofouling Expert Workshop was convened. Discussions involved participants from the marine renewable energy (MRE) industry, anti-fouling industry, academic institutions and regulatory bodies. The workshop aimed to consider both the benefits and negative effects of biofouling from engineering and ecological perspectives. In order to form an agenda for future research in the area of biofouling and the marine renewable energy industry, 119 topics were generated, categorised and prioritised. Identified areas for future focus fell within four overarching categories: operation and maintenance; structured design and engineering; ecology; and knowledge exchange. It is clear that understanding and minimising biofouling impacts on MRE infrastructure will be vital to the successful development of a reliable and cost effective MRE industry.

Keywords: wave, tidal, renewable energy, biofouling, marine growth

1. Introduction:

Marine Renewable Energy (MRE), the broad term for the wave and tidal stream energy industry, is expected to play an important part in meeting future energy needs world-wide, contributing to the renewable energy mix and therefore a more sustainable energy supply. The MRE industry is a growing sector which aims to harness the power of the world's seas. It is estimated that the global MRE market could grow to £76bn by 2050, and the UK is well placed to benefit from this [1]. It is estimated that the UK's wave and tidal power industry could provide up to 20% of the country's electricity needs [2] and, by 2035, be worth up to £6.1 billion to the UK economy [3]. The UK and Scotland in particular, are leading the world in MRE technology with more wave and tidal devices being tested in the UK than in the rest of the world combined [4].

When man-made structures such as MRE devices are submerged in the sea they are colonised by a wide variety of marine organisms that form complex biological communities (see Figure 1). This marine growth, or biofouling, is unwanted from an engineering perspective as it compromises design tolerances and requires additional maintenance activities. Studies on UK marine buoys have shown that biofouling can weigh more than 33kg per square metre [5]. Det Norske Veritas (DNV) guidelines for calculating environmental loads on fixed structures predict that marine growth on oil and gas platforms can reach 132.5kg per square metre [6]. Increased structural loading caused by biofouling can often have consequences for the structural integrity, efficiency, maintenance and functioning of marine structures [7,8,9]. Artificial structures can also be colonised by non-native species [10,11,12,13], making biofouling a potential biosecurity risk and devices possible vectors for species introduction.



Figure 1: Biofouling community on the side (left) and underside (right) of the Pelamis P2 device. [12]

Guidelines and regulations provide basic information to MRE developers on biofouling, but this information was not originally intended for the MRE industry. For example, the International Maritime Organization's guidelines on biofouling for ships and recreational craft [14,15] and the Code of Practice for the Wildlife and Natural Environment (Scotland) Act 2011 [16] are aimed at reducing the risk of transferring non-native species. Type approval and certification organisations include sections on marine growth in their guidance to inform design and certification of tidal energy turbines and arrays. Current guidance is derived from biofouling observations from the oil and gas industry, specifically in the Norwegian and North Sea. This is potentially a problem because oil and gas platforms provide very different environments for biofouling organisms than wave or tidal

devices. Wave and tidal devices are usually closer to shore, in a wider variety of locations including highly energetic environments, and can provide inherently different structural forms; all these factors effect biofouling development. Distance from shore for example, is known to have substantial impact on species composition of biofouling due to greater in food availability and larval/propagule supply closer to shore [17]. More data are required to ensure the information used to inform engineering guidelines is accurate and applicable for the MRE industry.

For engineers and device developers, biofouling can create a range of design and operational challenges that must be overcome to ensure device functionality, and for the industry to be considered an economically viable alternative to fossil energy production. Extensive marine growth on vulnerable or hydrodynamically optimised components, such as turbine blades, could have a disproportionately large influence on the mechanical performance of a device and the overall success of an MRE project [18,19,20].

Previous environmental research associated with MRE has often centred on interactions of devices with birds, mammals and cetaceans [21], and is driven by statutory environmental impact assessment requirements and public interest. Focussing on these areas of research has allowed the industry to gain the data required to support the licensing process for commercial operation. In the UK, the industry has now reached the point where multiple MRE devices are being tested in the ocean, and the first commercial arrays have been installed [22,23,24]. As device deployment length increases, attention is being drawn towards operational and maintenance issues, longevity of devices and increasing the efficiency of energy conversion. As a direct consequence, interest in the impacts of biofouling is growing within the MRE industry. Even so, there has been little crossover between engineering and ecology focussed research groups, with only occasional exceptions such as the EU funded ACORN project now emerging; this has meant that research progress has been slower than it could be and there is a risk of unnecessary repetition.

In an attempt to respond to the industry concerns, the Environmental Interactions of Marine Renewables (EIMR) Biofouling Expert Workshop was convened to bring together industrial, academic and regulatory participants. The workshop was held on the 22nd February 2016 in Edinburgh and it intended to consider both benefits and negative implications of biofouling from both engineering and ecological perspectives. A further aim of the workshop was to group and prioritise these biofouling related considerations in order to set a multi-disciplinary research agenda for biofouling on MRE devices. It is anticipated that this agenda will enable future development of industry guidelines and research on marine growth, will reflect industry standards and ultimately maximise operational and maintenance cost-savings, while promoting ecological benefits.

2. Methods and Context

The EIMR Biofouling Workshop took advantage of Scotland's world leading expertise in MRE development and testing and the presence of international experts due to the concurrent International Conference on Ocean Energy (ICOE) event. The organisers invited experts from across the MRE community to attend. The 18 attending delegates represented: MRE developers (3); academics (7); ecological consultancies (2); the anti-fouling industry (1); regulatory bodies (2) and research centres (3). All the participants had direct experience of MRE.

The workshop was split into three sessions. In session one, conversations were facilitated by using the “think, pair, share” technique, originally developed for classroom learning [25]. Participants were given five minutes to individually note down biofouling issues of greatest concern to them. In the next five minutes, they joined with a partner from the group to do the same. In the final ten minutes, groups of 4-6 participants came together to discuss these viewpoints and make any further notes. Notes took the form of individual observations, opinions and new research needs. Participants were encouraged to continue to create these as discussions progressed throughout the session. In the second workshop session, participants were split into four groups where the notes were brought together and categorised before conducting a prioritisation exercise (see Figure 2 and Table 1). Notes were ranked based on operational, financial and ecological implications, with each being assigned a score (1 = low importance, 2 = medium importance, 3 = high importance); the combined scores of the three categories resulted in an overall priority score for each note. In the final workshop session, the four groups came together to share their main prioritised areas and determine which should be considered the key areas for inclusion in a biofouling research agenda.

The categorised notes and prioritised key areas from the workshop are the basis of the agenda



presented in this paper¹.

Figure 2: Workshop participants discuss notes and categorisation

3. Workshop outputs

3.1. Categorisation of issues

Over the course of the workshop the participants generated 119 notes. Through group discussion these were grouped within four overarching categories: *operation and maintenance*; *structured*

¹ The workshop report can be viewed at www.uhi.ac.uk/en/merika/publications/ReportfromJenniferLoxtonEIMR2016.pdf

design and engineering; ecology; and knowledge exchange (see Figure 3). Within the first three of these categories further sub-categories were identified.

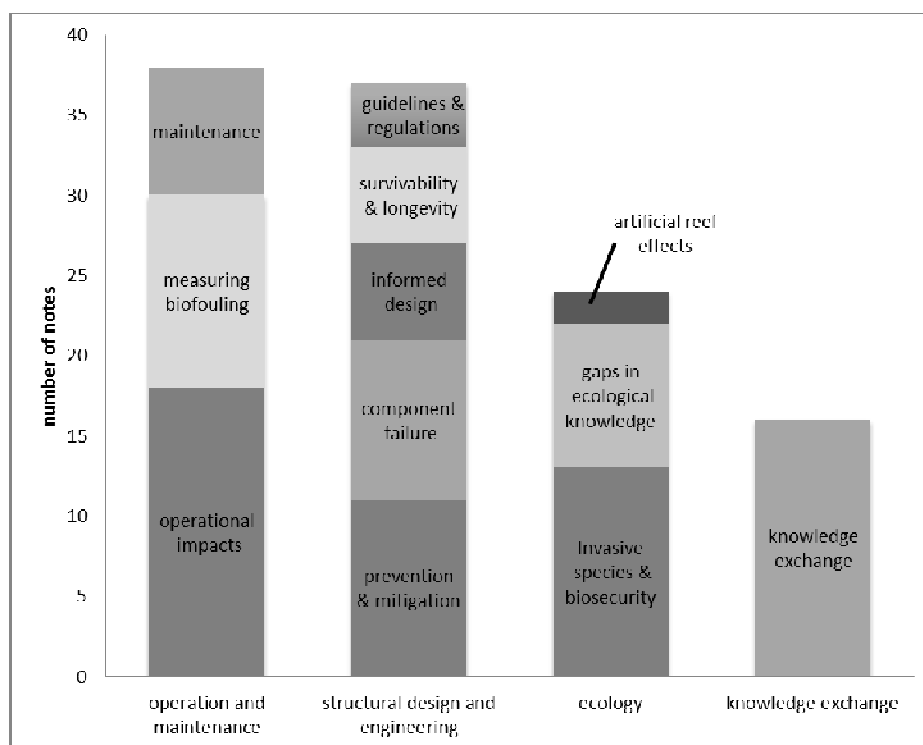


Figure 3: Categorisation of notes

The *operation and maintenance* category consisted of 38 notes concerned with issues, knowledge gaps and comments related to biofouling occurring on MRE devices post-deployment; the key topics summarised in these notes are included in Table 2. Further recurring themes were identified and the category was further divided into the sub-categories: *operational impacts* caused by biofouling (18); difficulties and lack of consistency around *measuring biofouling* (11); and biofouling impact on the regularity and methods of MRE device *maintenance* (9).

The *structural design and engineering* category consisted of 37 notes concerned with issues and knowledge gaps relating to biofouling considerations during the development/ pre-deployment phase of an MRE device; the key topics covered in these notes are summarised in Table 3. The themes within this category were more diverse resulting in five further sub-categories: *prevention and mitigation* of biofouling (10); *component failure* cause by biofouling (10); opportunities for *informed design*, taking into account biofouling (6); risks of reduced *survivability and longevity* of MRE devices due to biofouling impacts (6); and room for improvement in biofouling *guidelines and regulations* relating to MRE (4).

The *ecology* category comprised 27 notes highlighting both positive and negative environmental concerns, and gaps in existing ecological knowledge relating to biofouling and the MRE industry; the key topics covered in these notes are summarised in Table 4. The category was further divided into the sub-categories: *invasive species and biosecurity*, relating to the risk of invasive species presence and spread on fouled MRE devices and gaps and issues relating to biosecurity (13); the *gaps in*

ecological knowledge of biofouling species and communities (9); and the gaps in understanding of potential positive and negative *artificial reef effects* of fouled MRE devices (5).

The 16 notes in the *knowledge exchange* category highlighted opportunities for greater sharing and exchange of biofouling related knowledge between academia, MRE developers, support industries, other maritime industries, ecological consultancies, regulatory bodies and research centres.

3.2. Prioritisation of issues

Over the course of the workshop it became clear that the issues highlighted by various interest groups centred around the same themes, but as seen from a diversity of perspectives. For example, project developers wanted to understand whether the timing of device installation and maintenance (see 5.2) could affect the composition and severity of biofouling growth. Ecologists, meanwhile, wanted to improve the fundamental understanding of life-cycle characteristics of numerous important fouling species, recognizing that this information could be applied to optimise deployment and maintenance timelines (see 4.3).

A semi-quantitative ranking exercise was undertaken where the 45 issues/notes that were considered most important by the group were scored by the workshop participants; a score of 1, 2, or 3 (low, medium or high) was allocated for the financial, environmental, and operational importance of each note. This is illustrated in Table 1, which shows the final ranked sub-categories and the relative financial, operational, and environmental importance of each identified sub-category of notes. Sub-categories clearly linked to natural sciences, such as invasive non-native species and gaps in ecological knowledge, were ranked as more important from an environmental perspective, while maintenance, operational impacts of biofouling and device survivability and longevity were given substantially higher rankings from financial and operational perspectives. Interestingly, the informed design of devices was ranked equally highly across all sectors, as was knowledge exchange, reflecting a desire for multidisciplinary working at the planning and design stage of projects across all groups.

Table 1: Final ranked sub-categories and relative financial, operational and environmental scoring of each.

Sub-category	No. of notes	average importance score for prioritised issues in each sub-category (scale 1-3)			Overall rank
		Environmental	Operational	Financial	
Informed design	2	3	3	3	#1
Knowledge exchange	5	3	2.8	2.8	#2
Maintenance	5	2	3	3	#3
Survivability & longevity	4	2	3	3	#3
Measuring biofouling	5	2	3	2.8	#4
Prevention and mitigation	2	2.5	2.5	2.5	#5
Operational impacts	10	1.5	2.9	2.9	#6
Gaps in ecological knowledge	2	3	2	2	#7
Invasive species and biosecurity	5	2.8	1.8	2.4	#7
Component failure	3	1.7	2.7	2.7	#7
Artificial reef effects	2	2	1.5	1.5	#8
Guidelines & regulations	0	-	-	-	N/A

In the following sections we provide further detail and context around each of the different categories.

4. Operation and maintenance

4.1. Operational impacts

Biofouling can have technical implications on the operational performance of wave and tidal devices: it can increase the effective diameter of components, such as turbine blades, resulting in increased drag and inertia loads [26,8]; it also increases surface roughness and irregularities which change the flow around components [27], and result in altered lift and drag coefficients [28]. Increased drag and inertia can reduce the efficiency of energy extraction for some MRE designs, especially those that utilise turbine blades, resulting in sub-optimal energy extraction performance in between removal of biofouling during scheduled maintenance [18].

The consideration of biofouling is therefore an essential step when designing marine structures so that a device meets appropriate design tolerances and therefore ensures continued operational efficiency, despite the presence of biofouling. Biofouling, however, can be highly variable, differing between sites, seasons and devices [29]. To account for this, current MRE guidelines for biofouling aim to be conservative, which means that in many cases infrastructure may be over-engineered, although in rare cases they may also underestimate biofouling impact. Participants at the workshop noted the potential benefits of being able to consider site-specific biofouling data during the design phase in order to prevent both expensive over-engineering and unexpected operational impacts, and inform appropriate maintenance schedules that will keep devices running at their operational optimum; this is discussed further in Section 5.2.

4.2. Maintenance

Participants noted that biofouling is removed during maintenance intervals for a number of reasons: in order to reach components if it is restricting access; for health and safety reasons; or if biofouling has itself impeded the functionality or efficiency of the device or presents a risk to vulnerable components. Maintenance can be a costly procedure; planned and unplanned maintenance activities may account for up to 29% and 28% of an MRE projects total operating costs respectively [30]. Not only are maintenance activities expensive, but downtime, preventing devices from producing electricity, is also a key consideration. The application of antifouling solutions, such as paints and coatings, can help to decrease device maintenance requirements and costs associated with the removal of biofouling, in a similar way to that observed in the shipping industry [31]. However, the operational challenges associated with working in extreme environments may mean that existing anti-fouling technologies and practises may be suboptimal for the long-term deployments of MRE devices.

Recent research, such as that conducted by Nall [32] into the seasonal patterns of biofouling settlement and applications for biofouling mitigation, could help inform maintenance planning.

Future advances, such as the development and use of a biofouling sensor, may enable project operators to predict the frequency and urgency of maintenance interventions [33].

4.3. Measuring biofouling

It was agreed by the workshop participants that there are several advantages to measuring biofouling in a standardised and non-technical format. These advantages include:

- Allowing biofouling to be characterised at a site, prior to installation, to inform asset management costs
- Allowing device operators to take action to manage biofouling before it became established to a degree where removal was likely to impact on protective coating integrity or where biofouling impacts on the operation of the device; this will result in financial savings.
- Allow operators to distinguish between mechanically derived loss of efficiency of a device, or loss of efficacy resulting from accumulation of fouling
- At array scale, allowing device operators to prioritise management effort while also decreasing the incidence and cost of unnecessary maintenance procedures

Much of the data describing biofouling communities are collected opportunistically by remotely operated vehicles (ROV) during routine inspection activities [12], however, due to the lack of standardisation in these methods, data is often considered indicative and is not always officially reported or published. Improving the quality and consistency of this data will not only help individual developers better understand the extent of marine growth interacting with their projects, but if collected collaboratively in a standardised manner would also help marine industries understand patterns of marine growth in more detail. Therefore, the industry would benefit from the development of a Standard Operating Procedure that would allow data to be gathered in a manner that ensured the level of consistency and quality was adequate to allow future analyses across marine industries.

Table 2: Operation and Maintenance: highlights for future research

-
- What is the minimum level of information describing biofouling composition that is needed to inform management decisions?
 - How does biofouling impact the accuracy of sensors?
 - Can biofouling knowledge be used to minimize and predict maintenance?
 - Can safe and accepted techniques be developed for in-water clean and repair of biofouling damage?
 - Is a “little and often” cleaning approach feasible for biofouling?
 - Do fouling prevention coatings affect the maintenance approach?
 - How to accurately predict MRE device maintenance costs and longevity?
 - Is there a requirement for novel biofouling prevention, detection and mitigation measures?
 - What is the impact of biofouling loading on MRE devices and components?
 - How to characterise efficiency and quantify efficiency loss associated with biofouling?
 - What are the modes of action in efficiency impedance caused by biofouling?
 - What is the impact of biofouling on operational costs?
 - What is the impact of biofouling on performance?
 - Which types of biofouling are most problematic for the MRE industry?
 - Which biofouling species are most prevalent in different geographical areas?
 - What considerations should be taken around biofouling during retrieval and

decommissioning of MRE devices?

- Can installation of MRE devices be timed to minimise biofouling?
- There is a need to gather accurate information about the thickness, weight and roughness of marine growth.
- Can real-time sensing of biofouling be developed and integrated into MRE devices
- Can autonomous underwater vehicles be used for biofouling monitoring and clean-up?
- What are the real economic impacts of biofouling?

5. Structural design and engineering

5.1. Survivability and longevity

Workshop participants identified several aspects where biofouling might affect the survivability and longevity of marine renewable energy devices. Added mass, caused by marine growth, has the potential to affect the way structures move in the ocean. Added mass can alter both hydrodynamic coefficients and the weight of the structure. In a tidal flow this mass can cause or change “strumming”, vortex-induced vibration, occurrence [34] as it alters the “tuning” of the structure to the environment; and in heavy seas increased mass and inertia forces can amplify the impacts of “snatching”, which can result in increased forces on infrastructure. Although these forces are accounted for in the design phase, the additional mass of heavy biofouling could increase the rate of wear and fatigue loading of components [35]. Bio-corrosion was identified by the group as a further process capable of reducing infrastructure survivability, when multiple corrosion mechanisms such as sulphate reducing microbes [36] and crevice corrosion [37] were able to reduce the structural integrity of metals [38]; this may be further compounded by cathodic protection being compromised by biofouling. Tidal energy developers have anecdotally described instances of coating failure as a result of mechanical damage by biofouling organisms, which resulted in bio-corrosion of structures.

5.2. Informed design

The build-up of marine growth is known to result in severe operational issues and increased downtime across a range of marine industries, including MRE projects [39]. Attendees at the workshop suggested that many of these biofouling related issues could be minimised by using conservative design criteria during the design process. As a result *informed design* was ranked first among the prioritised categories, scoring the highest possible importance rating across environmental, operational and financial risk (see Table 1). While conservative design criteria may lead to additional expenditure for the MRE industry, attendees felt that it was important for manufacturers to design for the “worst-case” in terms of marine growth. Some workshop attendees further noted that this “over-designed” conservative approach could potentially negate the need for detailed information on biofouling at the design phase.

Perhaps the greatest gains in MRE device performance could be achieved through the selection of coatings that perform well against the specific biofouling found at the locations that devices are to be deployed. Site-specific knowledge of coating performance could be ascertained before devices are commercially installed, thus reducing expensive maintenance practices and operational downtime during the device lifetime.

5.3. Component failure

Attendees noted that effort is being made by industry and academia to improve understanding of MRE component failure rates. The European Marine Energy Centre (EMEC) has launched a marine component reliability testing programme [40], whilst individual universities specialise in the testing of sub-systems such as the reliability of mooring components [41]. Though there is a lack of thorough failure rate data in the MRE industry, it is well understood that marine growth may encourage the onset of component failure by increased mechanical wear and abrasion, unexpected service loads, material degradation and increased corrosion.

An example was given of the Albatern's Squid 6 Series device, an articulated wave energy converter, which generates power through a series of hydraulic pumping modules connected to a power take-off unit (see Figure 4). At present the hydraulic cylinders are exposed to seawater, making marine growth a particular concern. Though scrapers are installed to the fore of the cylinder to remove marine growth settlement on the piston shaft, any biological material remaining could cause additional wear to the hydraulic cylinder seals, potentially triggering premature component failure. Observations from initial sea trials have shown that marine growth failed to settle on piston shafts due to constant device movement, however the implications of long-term service periods are yet to be determined. Feasibility studies are being undertaken by Albatern to test the effectiveness of a flexible, waterproof membrane encasing the device's pumping modules and isolating them from the



seawater environment.

In general, the risk associated with component failure as a direct result of marine growth is yet to be quantified for the MRE industry. Long-term device operational data must be collected in conjunction with visual inspections and ongoing marine growth monitoring programmes in order to quantify this risk.

5.4. Prevention and mitigation

The reduction or prevention of biofouling build-up is a key management solution for mitigating negative technical and environmental impacts on marine energy devices. The main issues surrounding prevention and reduction of biofouling raised at the workshop focused on the cost, effectiveness, and toxicity of antifouling solutions.

There is currently a large variety of applicable commercially available marine antifouling systems. These encompass both toxic and non-toxic surface coatings [42,43], biofouling resistant materials [44], physical removal of biofouling [45] and seawater treatment in water intakes through electrolysis, chemical dosing, UV or ultrasound [46,47,48]. Few studies have tried to determine or predict the effectiveness of these systems in conjunction with the MRE industry and those that have relate to specific materials or components [49,48, 50]. Attendees highlighted recent research advances in this area including: research into how paint colours and coating types may influence the settlement of biofouling and the propensity of non-native species to be present [51]; and the trial of foul resistant coatings being testing on MRE devices.

Due to the high-costs of antifouling systems, the industry could benefit from a cost-benefit analysis of biofouling prevention/reduction, which includes all potential device components and materials. The industry might also benefit from sharing antifouling successes and failures between developers as a benchmarking tool.

Table 3: Structural design and engineering: highlights for future research

-
- What is the corrosion impact of biofouling on devices and moorings?
 - How can sensor heads be protected from biofouling?
 - How can anode fouling be prevented?
 - What is the impact of biofouling on hydraulic seals?
 - How best should the requirements for considering biofouling be communicated?
 - How can experience of component assembly, reliability and failure be shared?
 - How to prevent physical damage and fouling of moving components?
 - How to increase reliability of components under biofouling conditions?
 - How to maintain seal integrity under biofouling conditions?
 - How to design biofouling protection for seawater cooling intakes, pump pistons, seals and tool interfaces?
 - Is the cost of anti-fouling coatings financially viable for large areas and arrays of devices?
 - What are the best fouling prevention solutions for specific devices and components?
 - Which are the most resistant coatings to cavitation caused by biofouling?
 - Can biofouling prevention coatings be targeted to specific components?
 - How best to estimate the longevity of devices, sensors and components under biofouling conditions?
-

6. Ecology

6.1. Invasive species risk and biosecurity

The capability of marine renewable energy devices to facilitate the establishment and spread of non-native species was acknowledged as one of the major environment impacts of biofouling by academics and policy makers present at the workshop.

Non-native species are a known component of the biofouling assemblages on marine renewable energy device prototypes [52,13,12], and some non-native species are tolerant to biocidal antifouling coatings [53,54]. The fact that devices can provide habitat for fouling non-native species

highlights the potential for devices to aid their spread to new locations through larval dispersal via the stepping stone effect [55] and through the wet movement of devices [12]. For logistical reasons, many marine renewable device technologies are designed so they can be wet-towed between the energy extraction site and the storage/maintenance/fabrication harbours [56]. This potential pathway for non-native species transfer is of particular concern because harbours (especially large and busy ones) can be contaminated with a high number of non-native species [57,51].

Attendees agreed that in order to move forward to mitigate this impact, a general consensus on achievable biosecurity measures needs to be agreed between regulators, scientific bodies and developers, preferably before commercial operations begin. This consensus should relate to the requirements of national and international regulations that aim to control biological invasions (e.g. Wildlife and Natural Environment (Scotland) Act 2011, Marine Strategy Framework Directive, EU Invasive Alien Species Regulation, International Maritime Organization's guidelines on biofouling for ships and recreational craft [14,15]).

Recent research involving the identification and assessment of the risks associated with an activity or event with respect to the introduction of non-native species [58,59] may inform biosecurity planning for the MRE industry. Additional research has also been undertaken identifying the transfer pathways of non-native species that occur in the MRE industry [32,55].

6.2. Artificial reef effects

During the workshop artificial reef effects were predominantly recognized by members of the scientific community, who may be more conscious of these potential phenomena than developers and engineers.

The introduction of man-made structures in the marine environment provides new hard substrate for the settlement of benthic biofouling species. These benthic assemblages, which can reach tens of centimetres in thickness [60], in turn create a new habitat for colonization by epibenthic species and fish species searching for food and/or protection, leading to what is commonly referred to as artificial reef effects [61].

On one hand, artificial reef effects are considered to be ecologically positive: local biomass and biodiversity augmentation are promoted [61,62,63], and this increase in productivity can result in fish attraction and aggregation when compared to surrounding soft-bottom areas [64]; and if fisheries exclusion occurs then MRE devices can also become de-facto marine protected areas (MPAs) [65,66]. On the other hand, artificial reef effects can result in negative ecological impacts since their associated community composition may not be the same as natural reef communities in the same geographical area, which could lead to ecosystem changes as noted in research on the foundations of the Alghave offshore windfarm [67,68]. Artificial reef effects may vary depending on the existing ecosystem, geographical location and specific environmental features [69].

Despite ongoing research on artificial reef effects, the perception in the workshop was that these are not yet fully quantified or understood. The low ranking of artificial reef effects reflects this uncertainty during the prioritisation exercise when compared to other potential effects of biofouling.

6.3. Gaps in ecological understanding

Workshop discussions highlighted important ecological knowledge gaps specific to the MRE industry: fouling of moving parts and on novel materials is poorly understood, and there are limited prior studies on biofouling communities in high-energy wave and tidal environments. Improving dialogue between scientists, developers, and MRE test centre personnel will minimise lost opportunities to gather data and help prioritise research studies. It was also noted that once fouled, the recording accuracy of on-site marine data buoys decreased, affecting the quality of oceanographic information fed into MRE development planning. Sensors, which can detect biofouling cover and thickness on MRE devices, alerting project teams once a specific level has been reached, were suggested as a potential solution.

Many of these issues are compounded by the lack of taxonomic expertise in several of the more important fouling groups (e.g. bryozoans and hydroids) – training opportunities might address this. Even among well-studied groups (e.g. barnacles and macroalgae) fundamental gaps exist in our knowledge of reproductive and settlement timings.

Existing scientific literature and MRE-industry reports addressing issues identified at the workshop included: fouling on wave buoys [66] and moving parts unique to MRE devices [20]; artificial habitat creation by MRE infrastructure [21] and fouling of novel materials used in MRE devices [49]. Recent ecological studies of MRE sites and infrastructure have assessed biofouling composition at buoy locations in Scotland [5] and at different habitats targeted by MRE developers in Orkney [70]. It would be advantageous to the MRE and other industries if biofouling composition data could be applicable between sites and if predictive models are produced for geographic and temporal distribution of biofouling communities.

Recent research which was highlighted by attendees includes: experiments to quantify actual biofouling at MRE test sites across Europe under the MERIKA FP7 project; and a feasibility study for the building of a biofouling map to improve best estimates of biofouling for developers [29]. Additional topics for future focus include: improving stake-holder collaboration (e.g. removing barriers to data sharing); implementing more rigorous biofouling-related data collection; addressing fundamental performance issues such as boundary layer hydrodynamics in relation to biofouling [71], and emerging molecular techniques for early-detection of non-native species [72].

Table 4: Ecology: highlights for future research

-
- Do MRE devices/arrays act as artificial reefs?
 - What is the seasonal and temporal distribution of biofouling species?
 - Can the spatial distribution of biofouling communities be mapped?
 - What data is missing on growth rates and life traits of common biofouling species; how can these gaps be filled?
 - How can the number of people with biofouling taxonomy skills be increased?
 - How can the MRE industry prevent the translocation of invasive species during wet towing?
 - Can biosecurity be conducted in a collaborative way with other maritime industries?
 - What are the best tools for the MRE community to use for biosecurity planning?
 - Is action required when MRE devices act as habitats for non-native species which are already widely recorded in the geographical vicinity?
 - Are anti-fouling solutions tested on invasive non-native species?
 - How to prevent non-native species contamination of MRE devices during berthing and

maintenance in harbours?

- Does the organic waste released during in-water biofouling removal (e.g. power-washing) impact local ecology?
- What information do we need to predict biofouling community composition?
- What are the positive and negative impacts of biofouling on local ecology?

7. Knowledge exchange

Throughout the workshop the theme of 'knowledge exchange' surfaced repeatedly and was considered the second most important topic during the prioritisation exercise. Knowledge exchange is a growing field, which encourages the exchange of science and research between academia and non-academic end-users such as business and policymakers. It has been defined in a number of ways, including:

- ▶ *"A two-way process where scientists and individuals or organisations share learning, ideas, or experiences (...) creating a dialogue helps research to influence policy and practise" [73]*

The reciprocal nature of knowledge exchange activities is an important element that defines a successful activity: both parties benefit from the exchange. In the case of biofouling, each sector possesses information valuable to other sectors, and is also looking to receive information to further develop their work, business, policy, or research.

The group's discussion centred on understanding the motivations and needs of each stakeholder group around biofouling. The absence of effective knowledge exchange across these groups may have been related to the diversity of viewpoints and issues expressed, combined with a lack of common understanding to bridge these differences. For example, regulators expressed that their concerns and interest in the topic stemmed from existing environmental legislation and regulations, including the International Maritime Organisation regulations and the UK's Wildlife and Natural Environment (Scotland) Act 2011, which have requirements for the control of non-native species. Meanwhile, industry representatives were cognizant that they need to meet the requirements of this legislation, but prioritised performance and reliability of their devices in relation to reducing the overall cost of generating energy. Meanwhile, type approval and certification organisations wanted to ensure that their requirements and guidelines for biofouling were appropriate and accurate, while the academic community was focussed on applying their existing environmental knowledge and understanding to develop work-streams which increased the environmental knowledge base and which could be applied to optimising design, location, and regulation or marine developments.

To link these disciplines, an explicit pathway describing the flow of information between groups was developed (Figure 5). Marine biologists and ecologists have key information on biofouling species, their life histories, and their environmental preferences. This expertise is essential to advise on the likely biofouling communities to colonise marine renewable energy devices in different locations. Such information, alongside current guidance and regulations, can be used by engineers and device developers to 'design out' impacts from biofouling. Project developers can also use such understanding to improve anti-fouling coating selection and to better plan maintenance operations to minimise fouling impacts on the efficiency and power output of installed devices. Each of these then contributes to improving both the performance and reliability of device design. Where

quantitative information about biofouling makeup and biomass can be fed-back to ecologists and regulatory bodies, the process will improve, iteratively developing the capacity of the industry as a whole to predict and mitigate impacts from marine growth.

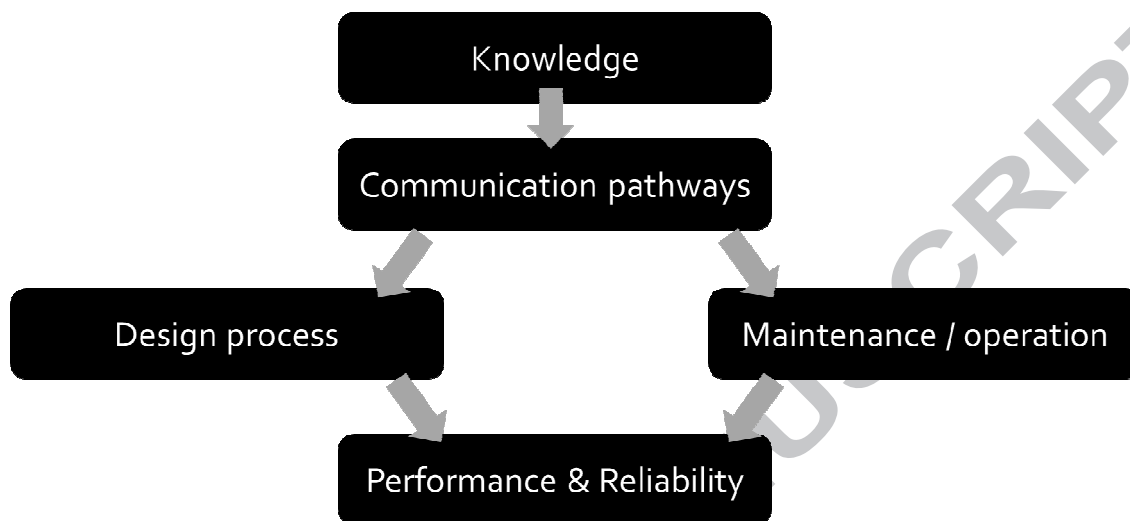


Figure 5: Pathway describing flow of information between groups

Developing mechanisms to enable this knowledge exchange is crucial. While informal pathways will continue to be important, more formal links between members of this community could help to reinforce and more rapidly advance this field. Formal links may take place through an online biofouling database populated by ecologists and biologists, an industry interest group, or dedicated innovation organisations. An example of an online network which may act as a template for a biofouling database is the European Marine Observation and Data Network (EMODnet), which assembles marine data, products and metadata to make them more accessible to both public and private users. Much can be learned from experiences from MRE front-runners, other maritime industries, as well as from the wealth of knowledge of the ecologists and regulators.

8. Conclusions/summary

This paper has advanced a multi-disciplinary agenda for biofouling research for the MRE industry. In the workshop upon which it is based, participants were given the opportunity to learn from each other's experiences and to collate concerns and impacts of biofouling in the MRE industry. Discussions took place at the cutting edge of research, development and deployment, involving participants from the MRE industry, anti-fouling industry, academic institutions and regulatory bodies.

Four main conclusions can be drawn from the workshop:

- **Operation and maintenance** methodologies and schedules are not making best use of existing biofouling knowledge from the scientific community. This could help reduce unnecessary costs and increase the efficiency of MRE devices.

- MRE **device and component designs** currently use “broad-brush” conservative estimates of biofouling. There may be benefits that could be achieved by making design choices using accurate site-specific data on biofouling e.g. choice of coating.
- There are still gaps in fundamental **biological and ecological knowledge** for some biofouling species and of biofouling communities in high energetic areas; therefore potential ecological impacts are not fully understood.
- Current methods of **communication** are failing to facilitate the effective and timely exchange of knowledge between MRE stakeholders, particularly industry and academia.

The wider purpose of our work has been to identify the areas for industrially relevant biofouling research, which responds to and reaches beyond existing MRE research themes. While current biofouling research often focuses on tackling immediate problems encountered in individual MRE developments, cross-disciplinary research on biofouling has the potential to contribute to cost savings in multiple areas within the wider MRE sector whilst preventing negative impacts to the environment.

Underlying this agenda is the opportunity for knowledge exchange to enable biofouling to be considered in MRE development, right from its early stages, in which biofouling data can be not merely a *post hoc* maintenance issue but can be considered in design, component and site selection and allow for accurate productivity, maintenance and longevity predictions.

It is clear that understanding and minimising biofouling impacts on MRE infrastructure is vital to the successful development of a reliable and cost effective MRE industry, which can viably compete with more traditional methods of energy generation. As the emerging MRE sector continues to grow and mature, collaborative and future-orientated biofouling research has many roles to play.

Acknowledgements

The authors would like to thank all attendees to the Environmental Interactions of Marine Renewables (EIMR) Biofouling Expert Workshop for their contribution. The EIMR 2016 workshops were held in cooperation with Annex IV, ICIT Heriot Watt, ORJIP, ICOE 2016, Marine Scotland and MERIKA and the authors thank this consortium for their support. JL, TS, IM and CRN were supported by the MERIKA project which received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 315925. RM and JL acknowledge the support of NERC Awards NE/M006999/1 (KEWTE) and NE/P006566/1 respectively. TS and IM were supported by the RICORE project, which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n° 646436. JL, TV, RM and AM would like to acknowledge the Offshore Renewable Energy Catapult for their encouragement and support.

References

- [1] Department of Transport. Maritime Growth Study: keeping the UK competitive in a global market, 2015.
- [2] Department of Energy and Climate Change, Wave and Tidal energy: part of the UK's energy mix. <http://www.gov.uk/guidance/wave-and-tidal-energy-part-of-the-uks-energy-mix>, 2013 (accessed 06/06/2016).

- [3] Renewable UK, Wave and Tidal Energy in the UK: Conquering challenges, generating growth. <http://www.renewableuk.com/download.cfm/docid/40714D87-D50E-4265-B45EBD1E1E573624>, 2013 (accessed 06/06/2016).
- [4] Ernst & Young. Rising tide: Global trends in the emerging ocean energy market, 2013.
- [5] A. Macleod, M. Stanley, J. Day, E. Cook, Biofouling community composition across a range of environmental conditions and geographical locations suitable for floating marine renewable energy generation, *Biofouling*. 32:3 (2016) 261-276.
- [6] Det Norske Veritas, Recommended Practice DNV-RP-C205: Environmental Conditions and Environmental Loads, 2014.
- [7] A. Theophanatos, J. Wolfram, Hydrodynamic loading on a macro-roughened cylinders of various aspect ratios, *Journal of offshore mechanics and Arctic engineering*. 111 (1989) 214-222.
- [8] I. Jusoh, J. Wolfram J, Effects of marine growth and hydrodynamic loading on offshore structures. *Jurnal Mekanikal*. 1 (1996) 77-96.
- [9] Det Norske Veritas, Design of offshore wind turbine structures DNV-OS-J101, 2013.
- [10] T.M. Glasby, S.D. Connell, M.G. Holloway, C.L. Hewitt, Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions, *Marine Biology*. 151:3 (2007) 887-895.
- [11] F. Mineur, E.J. Cook, D. Minchin, K. Bohn, A. Macleod, C.A. Maggs, Changing coasts: marine aliens and artificial structures, *Oceanography and marine biology – an annual review*. 50 (2012) 189-234.
- [12] C.R. Nall, M.L. Schläppy, A.J. Guerin, Characterisation of the biofouling community on a floating wave energy device. *Biofouling*. 33:5 (2017) 379-396.
- [13] J.L. Loxton, C.R. Wood, J.J.D. Bishop, J.S. Porter, M. Spencer Jones, C.R. Nall, Distribution of the invasive bryozoan *Schizoporella japonica* in Great Britain and Ireland and a review of its European distribution, *Biological Invasions*, (2017).
- [14] Marine Environment Protection Committee, 2011 Guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species. Resolution MEPC.207(62). MEPC 62/24/Add.1. [http://www.imo.org/en/OurWork/Environment/Biofouling/Documents/RESOLUTION%20MEPC.207\[62\].pdf](http://www.imo.org/en/OurWork/Environment/Biofouling/Documents/RESOLUTION%20MEPC.207[62].pdf), 2011 (accessed 09.05.2016).
- [15] Marine Environment Protection Committee, Guidance for minimizing the transfer of invasive aquatic species as biofouling (hull fouling) for recreational craft. MEPC.1/circ.792. <http://www.imo.org/en/OurWork/Environment/Biofouling/Documents/MEPC.1-Circ.792.pdf>, 2012 (accessed 09.05.2016)
- [16] Scottish Government, Code of Practice on Non-Native Species. Made by the Scottish Ministers under section 14C of the Wildlife and Countryside Act 1981. Scottish Government, Edinburgh. [.http://www.gov.scot/Resource/0039/00398608.pdf](http://www.gov.scot/Resource/0039/00398608.pdf), 2012 (accessed 09.05.2016).

- [17] P.W. Sammarco, A.D. Atchison, G.S. Boland, Expansion of coral communities within the northern Gulf of Mexico via off- shore oil and gas platforms, *Marine Ecology Progress Series* 280 (2004) 129–43.
- [18] J.A.C. Orme, I. Masters, R.T. Griffiths, Investigation of the effect of biofouling on the efficiency of marine current turbines. In: C. French (Ed.), *Proc Int Conf Mar Renew Energies (MAREC 2001)*. London, UK: Institute of Marine Engineers, 2001, pp. 91-99.
- [19] C. Anderson, Pelamis WEC – Main body structural design and materials selection. Report prepared for Ocean Power Delivery Ltd as part of the DTI New and Renewable Energy Programme. Edinburgh, UK, 2003.
- [20] R. Tiron, K. Doherty, T. Whittaker, An Experimental Study of the Hydrodynamic Effects of marine growth on wave energy convertors. *Proc ASME 2013 32nd Int Conf Ocean Offshore Arct Eng.* Nantes, France. (2014).
- [21] R.G. Miller, Z.L. Hutchison, A.K. Macleod, M.T. Burrows, E.J. Cook, K.S. Last, B. Wilson, Marine renewable energy development: assessing the benthic footprint at multiple scales, *Front Ecol Environ.* (2013).
- [22] Scottish Renewables, *Marine Milestones 2014/2015 Report*, 2015.
- [23] Atlantis Resources Ltd, *Meygen update 6 March 2017. Press Release*, 2017.
- [24] Nova Innovation, *Nova Innovation deploys world's first fully operational offshore tidal array in Scotland*, Press release. 2016.
- [25] F. Lyman, Think-pair-share: An expanding teaching technique. *MAA-CIE Cooperative News*, 1:1 (1987) 1-2.
- [26] T. Yan, W. Yan, Y. Dong, H. Wang, Y. Yan, G. Liang, Marine fouling of offshore installations in the northern Beibu Gulf of China. *International Biodeterioration & Biodegradation* 58:2 (2006) 99-105.
- [27] M. Zeinoddini, A. Bakhtiari, M. Ehteshami, M.S. Seif, Towards an understanding of the marine fouling effects on VIV of circular cylinders: response of cylinders with regular pyramidal roughness. *Applied Ocean Research*, 59 (2016) 378-394.
- [28] F.K. Fuss, The effect of surface skewness on the super/postcritical coefficient of drag on roughened cylinders. *Procedia Engineering*, 13 (2011) 284-289.
- [29] R.G. Miller, A.K. Macleod, *Marine Growth Mapping and Monitoring: Feasibility of Predictive Mapping of Marine Growth. A report by SAMS Research Services Ltd to the Offshore Renewable Energy Catapult*, 2016.
- [30] Carbon Trust, *Cost of Energy: capital, operating and maintenance costs*, 2006.
- [31] M.P. Schultz, J.A. Bendick, E.R. Holm, W.M. Hertel, Economic impact of biofouling on a naval surface ship, *Biofouling*, 27 (2011) 87-98.

- [32] C.R. Nall, A.J. Guerin, E.J. Cook, Rapid assessment of marine non-native species in northern Scotland and a synthesis of existing Scottish records, *Aquatic Invasions*, 10:1 (2015) 107–121.
- [33] A. Yunnice, T. Vance, R. Ramsden, Marine Growth Mapping and Monitoring: Feasibility of Sensor Development for Monitoring Marine Growth. A report by PML Applications to the Offshore Renewable Energy Catapult, 2016.
- [34] O.M. Griffin, Vortex-Induced Vibrations of Marine Cables and Structures (No. NRL-5600). Naval research laboratory, 1985.
- [35] T.R. Vance, T. Fileman, ETI MA1001 – Reliable data acquisition platform for Tidal (ReDAPT) project: ME8.5 “Final Report”, Energy Technologies Institute, 2014.
- [36] R. Liang, Microbiologically Influenced Corrosion of Carbon Steel in Sulfidogenic Environments: The Link to Thiosulfate Reduction and Biological Stability of Alternative Fuels. PhD thesis. University of Oklahoma, 2015.
- [37] M. Eashwar, G. Subramanian, P. Chandrasekaran, K. Balakrishnan, Mechanism for Barnacle-Induced Crevice Corrosion in Stainless Steel, *Corrosion*, 48:7 (1992) 608-612.
- [38] I.B. Beech, J.A. Sunner, K. Hiraoka, Microbe-surface interactions in biofouling and biocorrosion processes, *International microbiology*, 8:3 (2010) 157-168.
- [39] A. Uihlein, D. Magagna, Wave and tidal current energy – a review of the current state of research beyond technology, *Renewable and sustainable energy reviews*, 58 (2016) 1070-1081.
- [40] EMEC, Marine Energy Component Analysis – case study. Prepared by EMEC for the Offshore Renewable Energy Catapult, 2016.
- [41] P.R. Thies, L. Johanning, Development of a marine component testing facility for marine energy converters, 3rd Int. conference on Ocean Energy (ICOE 2010), Bilbao, 6th - 8th Oct 2010, Proc. of 3rd Int. Conference on Ocean Energy [ICOE], (2010).
- [42] E. Almeida, T.C. Diamantino, O. de Sousa, Marine paints: The particular case of antifouling paints, *Progress in Organic Coatings* 59 (2007) 2–20.
- [43] J.E. Gittens, T.J. Smith, R. Suleiman, R. Akid, Current and emerging environmentally-friendly systems for fouling control in the marine environment, *Biotechnology Advances*, 31:8 (2013) 1738–1753.
- [44] C.A. Powell, H.T. Michels, Copper-nickel alloys for seawater corrosionresistance and antifouling – a state of the art review, *Corrosion*, 2000 (2000) Paper 00627.
- [45] R.C. Roche, J.M. Monnington, R.G. Newstead, K. Sambrook, K. Griffith, R.H.F. Holt, S.R. Jenkins Recreational vessels as a vector for marine non-natives: developing biosecurity measures and managing risk through an in-water encapsulation system, *Hydrobiologia* 750:1 (2014) 187–199.
- [46] C. López-Galindo, J.F. Casanueva, E. Nebot, Efficacy of different antifouling treatments for seawater cooling systems, *Biofouling* 26:8 (2010) 923–930.

- [47] D. Rubio, J.F. Casanueva, E. Nebot, Assessment of the antifouling effect of five different treatment strategies on a seawater cooling system, *Applied Thermal Engineering* 85 (2015) 124–134.
- [48] S. Blair, D. Roberts, M. Scantlebury, B. Eden, The Potential Impacts of Biofouling on a Wave Energy Converter Using an Open Loop Seawater Power Take Off System. Report prepared for Aquamarine Power, 2014.
- [49] B.L. Polagye, J. Thomson, Screening for biofouling and corrosion of tidal energy device materials: in-situ results from Admiralty Inlet, Puget Sounds, Washington. National Marine Renewable Energy Center Report no. 1. Seattle: NNMREC, 2010.
- [50] ASTM D3623-78a (Reapproved 2012), Standard Test Method for Testing Antifouling Panels in Shallow Submergence, ASTM International, West Conshohocken, PA, United States
- [51] C.R. Nall CR, Marine non-native species in northern Scotland and the implications for the marine renewable energy industry. PhD Thesis. University of Aberdeen, UK, 2015.
- [52] J.S. Ryland, R. Holt, J. Loxton, M.E. Spencer Jones, J.S. Porter, First occurrence of the non-native bryozoan *Schizoporella japonica* Ortmann (1890) in Western Europe, *Zootaxa* 3780:3 (2014) 481–502.
- [53] O. Floerl, T.K. Pool, G.J. Inglis, Positive Interactions between Nonindigenous Species Facilitate Transport by Human Vectors, *Ecological Applications* 14:6 (2004) 1724–1736.
- [54] R.F. Piola, E.L. Johnston, Comparing differential tolerance of native and non-indigenous marine species to metal pollution using novel assay techniques, *Environmental Pollution* 157:10 (2009) 2853–2864.
- [55] T.P. Adams, R.G. Miller, D. Aleynik, M.T. Burrows, Offshore marine renewable energy devices as stepping stones across biogeographical boundaries, *Journal of Applied Ecology* 51 (2014) 330–338.
- [56] Highlands and Islands Enterprise, The Highlands and Islands marine renewables infrastructure plan. Strategic environmental assessment, 2014.
- [57] J.T. Carlton, Patterns of transoceanic marine biological invasions in the Pacific Ocean. *Bulletin of Marine Science* 41:2 (1987) 452–465.
- [58] E.J. Cook, R.D. Payne, A. Macleod, S.F. Brown, Marine Biosecurity: protecting indigenous marine species, *Research and Reports in Biodiversity Studies* 5 (2016) 1-14.
- [59] R. Payne, E.J. Cook, A. Macleod, Marine Biosecurity Planning - Guidance for Producing Site and Operation-Based Plans for Preventing the Introduction of Non-Native Species. Report by SRSI to the Firth of Clyde Forum and Scottish Natural Heritage, 2014.
- [60] J.B. Bram, H. M. Page, J.E. Dugan, Spatial and temporal variability in early successional patterns of an invertebrate assemblage at an offshore oil platform, *Journal of Experimental Marine Biology and Ecology* 317:2 (2005) 223-237.

- [61] R. Inger, M.J. Attrill, S. Bearhop, A.C. Broderick, W.J. Grecian, D.J. Hodgson, C. Mills, E. Sheehan, S.C. Votier, M.J. Witt, B.J. Godley, Marine renewable energy: potential benefits to biodiversity? An urgent call for research *Journal of Applied Ecology* 46:6 (2009) 1145-1153.
- [62] E.A.S. Linley, T.A. Wilding, K. Black, A.J.S. Hawkins, S. Mangi, Review of the reef effects of offshore wind farm structures and their potential for enhancement and mitigation. Report from PML Applications Ltd. and the Scottish Association for Marine Science to the Department for Business, Enterprise and regulatory Reform (BERR), 2007.
- [63] M.C. Ashley, S.C. Mangi, L.D. Rodwell, The potential of offshore windfarms to act as marine protected areas – A systematic review of current evidence *Marine Policy* 45 (2014) 301-309.
- [64] D. Wilhelmsson, T. Malm, Fouling assemblages on offshore wind power plants and adjacent substrata, *Estuarine, Coastal and Shelf Science* 79:3 (2008) 459-466.
- [65] O. Langhamer, D. Wilhelmsson, Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes - a field experiment *Marine Environmental Research* 68:4 (2009) 151-157.
- [66] O. Langhamer, D. Wilhelmsson, J. Engström, Artificial reef effect and fouling impacts on offshore wave power foundations and buoys - a pilot study, *Estuarine, Coastal & Shelf Science* 82 (2009) 426-432.
- [67] R. Krone, L. Gutow, T. Joschko, A. Schröder, Epifauna Dynamics at an Offshore Foundation - Implications of Future Wind Power Farming in the North Sea, *Marine Environmental Research* 85 (2013) 1-12.
- [68] R. Krone, L. Gutow, T. Brey, J. Dannheim, A. Schröder, Mobile Demersal Megafauna at Artificial Structures in the German Bight - Likely Effects of Offshore Wind Farm Development, *Estuarine, Coastal and Shelf Science* 125 (2013) 1-9.
- [69] O. Langhamer, Artificial Reef Effect in relation to Offshore Renewable Energy Conversion: State of the Art, *The Scientific World Journal* 8 (2012).
- [70] A. Want, J.S. Porter, Biofouling solutions for marine renewables: knowledge network development. Energy Academy FLEDGE Report, Heriot-Watt University, 2015.
- [71] M.A. Shields, D.K. Woolf, E.P.M. Grist, S.A. Kerr, A.C. Jackson, R.E. Harris, M.C. Bell, R.A. Beharie, A. Want, E. Osalusi, S.W. Gibb, J.C. Side, Marine Renewable Energy: The ecological implications of altering the hydrodynamics of the marine environment, *Ocean and Coastal Management* 54 (2011) 2-9.
- [72] X. Pochon, A. Zaiko, G.A. Hopkins, J.C. Banks, S.A. Wood, Early detection of eukaryotic communities from marine biofilm using high-throughput sequencing: an assessment of different sampling devices, *Biofouling* 31 (2015) 241-251.
- [73] ESRC, <http://www.esrc.ac.uk/collaboration/knowledge-exchange/>, 2016 (accessed 17/05/2016).

Highlights

- Biofouling causes a range of issues for marine renewable energy (MRE) stakeholders
- An agenda for biofouling research for the MRE industry is proposed
- Biofouling data could reduce operation & maintenance cost and increase efficiency
- Site-specific biofouling data could aid the design of MRE devices and components
- Current methods of knowledge exchange are insufficient between MRE stakeholders

ACCEPTED MANUSCRIPT